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THEORY OF THE AURORAL MAGNETOSPHERE

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Abstract

The aurora has come to be understood as a manifestation of energy transfer and plasma transfer from the solar wind to the magnetosphere. The auroral oval seems to be a mapping of the boundary layer that lies just inside the magnetospheric surface, which consists of the magnetopause and neutral sheet. The auroral oval is consequently a region of reversal for the meridional (r, θ) component of the magnetospheric convection electric field and thus a region of strong shear in the plasma drift-velocity field. The velocity shear seems to account for the formation of eddies in the auroral "curtain". Moreover, the kinematical impedance associated with hot auroral plasma in magnetic-mirror geometry makes it impossible for the reversal of the perpendicular (meridional) electric field across a narrow region of latitude to occur without the formation of a large parallel electric field. The signature of the parallel electric field is such as to produce upgoing ion beams and precipitating electron beams in the PM (afternoon-evening) sector of local time, and to account for the polarity of Region-I currents as a function of local time. Region-II currents are return currents that result from the need to conserve current despite the diminution of ionospheric electric field with decreasing latitude. The strength of the parallel electric field, and consequently of all related auroral phenomena, is dependent on the "reconnection efficiency" with which the interplanetary (solar-wind) electric field is admitted to the magnetosphere. The tangential component of the electric field is required (by Maxwell's equations) to be continuous across the magnetopause and (moreover) admits solar-wind plasma to the magnetosphere. The admitted plasma (along with that drawn from the ionosphere by parallel electric fields) becomes part of the plasma sheet and is available for precipitation, either in discrete arcs (in response to strong parallel electric fields) or in the diffuse aurora (via wave-induced pitch-angle scattering). However, the diffuse aurora can experience a spatial intensity modulation caused by non-convective instabilities in the underlying plasma and magnetic-field configuration. Such phenomena (e.g., mirror instability) can lead to bands of particle precipitation aligned with the magnetospheric convection pattern, as in the pre-dawn sector.

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1. INTRODUCTION

This is supposed to be an introductory review of the aspects of magnetospheric theory that have a bearing on auroral phenomena. The discrete-auroral oval seems to be a mapping (along magnetic-field lines) of a boundary layer at (or just inside) the magnetospheric surface. The magnetospheric surface consists of the magnetopause and "neutral" sheet. The cross-magnetospheric "convection" electric field necessarily undergoes a sharp reversal (a near-discontinuity) in its meridional (r,θ) component in this boundary layer and across magnetic-field lines that map to the boundary layer. The cold collisional ionospheric plasma near the foot of the auroral flux tube is unable to support such a near-discontinuity in the normal (to $\underset{\sim}{B}$) component of an electrostatic field without the concomitant appearance of an electric-field component parallel to $\underset{\sim}{B}$. This inability is a consequence of current conservation, Pedersen conductivity, and Ohmic resistivity in the ionosphere (Chiu, 1974). Moreover, the hot collisionless magnetospheric plasma in the same flux tube supports such a parallel (to $\underset{\sim}{B}$) electric field and thus causes the $E_{\parallel}$ to remain substantial even at altitudes up to about 10^4 km. The signature of this $E_{\parallel}$ (upward in the PM sector, downward in the AM) is plainly evident in ion and electron distributions observed from the S3-3 satellite (Mizera et al., 1976; Mizera and Fennell, 1977).

The ability of hot plasma to support a parallel electric field is a consequence of mirror forces which follow from the inhomogeneity of $|\underset{\sim}{B}|$, as Alfvén and Fälthammar (1963) proposed. Models based on a uniform magnetic field (e.g., Swift, 1975, 1976) lack this essential feature and so are more difficult to understand. Models of the parallel electric field supported by progressively realistic charged-particle populations in mirror geometry have been formulated by Persson (1966), Lemaire and Scherer (1974), and Chiu and Schulz (1978). However, these magnetic-mirror models were essentially one-dimensional and thus did not explain why the parallel electric field appears in conjunction with reversals of the perpendicular electric field, e.g., in the electric-field observations of Mozer et al. (1977) when these are combined with charged-particle observations (as reviewed by Cornwall and Schulz, 1979). However, an early one-dimensional magnetic-mirror model formulated by Knight (1973) yielded voltage-current characteristics for an auroral flux tube. Lyons (1980) inferred a kinematical impedance from similar characteristic curves and used this (together with current conservation) to map the correspondence of high-altitude electric fields perpendicular to $\underset{\sim}{B}$ with the auroral potential structure inferred from particle and field observations. It is not entirely clear that the kinematical impedance associated with mirror forces can be treated for all intents and purposes as an Ohmic resistance, and so Chiu and Cornwall (1980) analyzed the more complicated two-dimensional problem by means of Poisson's equation. Their calculation yielded a reasonable width scale for auroral arcs and "inverted-V" structures but may have left some loose ends in the treatment of magnetosphere-ionosphere coupling at low altitudes. Swift (1979) had meanwhile extended his previously cited "oblique shock" calculations to the case of an inhomogeneous $\underset{\sim}{B}$ field and thereby obtained an interesting representation of the auroral potential structure, although the cross-field width scale remains an adjustable parameter of his model.

The diffuse aurora occurs equatorward of the discrete aurora, and therefore on closed field lines. The diffuse aurora is customarily attributed to a near-equatorial scattering of geomagnetically trapped particles (constituting the inner part of the plasma sheet, or equivalently the outer part of the ring current) rather than to the action of a parallel electric field. The diffuse-auroral region seems more nearly symmetric in local time

than the discrete-auroral oval, so that the two are essentially adjacent at midnight and well separated at noon. Both types of aurora receive particles from the plasma sheet, but the diffuse-auroral region seems to track more nearly the drift shell of a particle that mirrors near the edge of the loss cone. The enhancement of diffuse-auroral precipitation that occurs in the mid-morning sector seems reasonable in view of the energization that electrons would have experienced in drifting toward that sector (i.e., toward dawn and therefore against the convection electric field) from midnight (e.g., Jentsch, 1976). An interesting question is how the diffuse aurora can be modulated in space and time to produce the patches and pulsations that are commonly observed in it. An equally interesting question is how the discrete aurora can be modulated in space and time so as to procedure the convoluted (and sometimes multiple) arc structures that are commonly observed there.

2. ELECTRIC-FIELD MAPPING

It is well known that the solar-wind velocity vector makes a considerable angle with the interplanetary magnetic field. The non-alignment occurs in part because of the rotation of the sun (which creates the Parker spiral through a "garden-hose" effect) and in part because of transitory disturbances of the solar-wind plasma and magnetic field (e.g., following a solar flare). The consequence of such effects is an electric field in interplanetary space. If the surface of the magnetosphere were to behave as a perfect conductor, then the magnetosphere would be impervious to this interplanetary electric field, and interplanetary magnetic field lines would be diverted so as to slide around the magnetopause rather than penetrate it. This idealization, known as the "closed" magnetosphere, comes close to being realized only when the solar wind has been very quiet and the interplanetary $\underset{\sim}{B}$ field has been predominantly northward (at least in its north-south component relative to the earth's dipole) for several days. Conversely, if the surface of the magnetosphere were to behave as a perfect insulator and the magnetosphere as a perfect vacuum, then the interplanetary electric field would penetrate the magnetosphere undiminished. This idealization is never realized, although it was used by Dungey (1961) to illustrate an extreme example of what has come to be known as the "open" magnetosphere.

The truth, as usual, lies somewhere between the two extreme idealizations. The magnetosphere admits perhaps 20% of the interplanetary electric field when the interplanetary $\underset{\sim}{B}$ field has a strong southward component, but only a few percent of the interplanetary electric field when the interplanetary magnetic field has a northward component. Schulz (1980) has shown how a modest re-interpretation of the model used by Dungey (1961) can accommodate the admission of an arbitrary fraction ε of the interplanetary electric field into the magnetosphere. The process whereby a fraction of the interplanetary electric field is admitted into the magnetosphere is known as "reconnection" because it requires (at least in a geometrically realistic model of the magnetosphere) a blurring of the distinction between interplanetary field lines and magnetospheric field lines in the description of magnetic topology. It is not yet clear whether the process called "reconnection" requires some plasma instability (such as the tearing mode) to operate, or whether instead the low density characteristic of interplanetary and magnetospheric plasma makes partial admission of the interplanetary electric field into the magnetosphere inevitable. A third alternative, proposed by Lemaire (1979), is that the solar wind must already have small-scale irregularities upstream of the magnetopause in order for "reconnection" to occur.

The foregoing emphasis on electric-field mapping is consistent with the definition of "reconnection" proposed by Vasyliunas (1975) : the process whereby plasma flows across a surface that separates regions containing topologically different magnetic-field lines. The separatrix in this case consists of the magnetospheric surface and its mapping along magnetic field lines to the auroral oval. The plasma flow is the $\mathbf{E} \times \mathbf{B}$ drift associated with the tangential component of the electric field at the separatrix, for in the absence of such a tangential component the admission of any fraction of the interplanetary electric field into the magnetosphere would violate the electrostatic continuity laws imposed by Maxwell's equations.

Reconnection thus creates a dawn-to-dusk potential drop proportional to the southward component of the interplanetary magnetic field. This can modify magnetopause currents, energize particles in the plasma sheet, and initiate Birkeland currents (parallel to $\mathbf{B}$) to the extent that the earth's ionosphere will accept them. Indeed, the latitudinal inhomogeneity of the "convection" electric field at ionospheric altitude combines with the requirement of current conservation (Ampère's law) to produce a fairly complex pattern of Birkeland currents. The main current (called Region-I current) enters the ionosphere in the AM sector of the discrete-auroral oval and exits in the PM sector, as one might expect from the direction of the potential drop. Associated with this is a fairly uniform Pedersen current across the polar cap. However, the Pedersen current at sub-auroral latitudes is so inhomogeneous that perhaps 90% of it must return to the magnetosphere rather than flow from the AM sector to the PM sector. This return current, which occurs equatorward of the auroral arc, is known as the Region-II current.

Volland (1975) has constructed a model electrostatic potential for the convection electric field, so as to illustrate the foregoing ideas very well. He has introduced, in effect, a critical latitude corresponding to the auroral oval, across which the normal component of the ionospheric electric field is discontinuous. The electric field in his model is uniform across the polar cap but not at sub-auroral latitudes. Indeed, his sub-auroral ionospheric electric field decreases sharply in magnitude from a maximum at the critical latitude to a broad minimum at the equator. The sub-auroral Pedersen current thus has a strong equatorward component that the spatially decreasing electric field cannot sustain. Current conservation requires, therefore, the appearance of Region-II Birkeland currents along the magnetic field. The discontinuity of the normal component of $\mathbf{E}$ across the auroral oval in the model of Volland (1975) is realistic on the large (magnetospheric) scale but leads to difficulty with current conservation unless a large parallel (to $\mathbf{B}$) electric field is added at the site of discontinuity (*cf.* Chiu, 1974). The parallel electric field would have to be downward in the AM sector and upward in the PM sector, in accordance with the flow of Region-I currents and with the observed (Ghielmetti *et al.*, 1978) prevalence of upgoing ion beams in the PM sector. Nevertheless, the field-mapping results of Lyons (1980) and the direct observations of Mozer *et al.* (1977) cast doubt on the proposition that the discontinuity of the convection electric field itself is sufficient to produce the aurora. It seems from these studies that a smaller-scale discontinuity of larger magnitude is both required and present. Lemaire (1981) has suggested that the structure of the charge layer at the boundary of the magnetosphere itself must be considered and would be profitable to investigate in this context.

3. MODULATIONS AND IRREGULARITIES

The near-discontinuity of the perpendicular electric field across the auroral oval suggests a strong shear in the convection-velocity field there. One should expect the Kelvin-Helmholtz instability to occur, and indeed it seems to. The folds and eddies that make the discrete aurora look like a curtain when seen from afar would be an expected consequence of the Kelvin-Helmholtz instability (Hallinan, 1970). However, these could alternatively result from the Kruskal-Shafranov instability, an MHD phenomenon that causes a current sheet to buckle when the current density becomes too large (Hasegawa, 1970; Forslund, 1970). The buckling occurs as a consequence of mutual attraction between parallel currents. Construction of an MHD equilibrium for an auroral current sheet suggests therefore that the sheet should become thinner as the current is increased. This consideration perhaps accounts for the sharper definition of an active auroral curtain as compared with a quiet auroral arc. Mutual attraction between parallel currents can also lead to the filamentation of a current sheet, as in the case of a tearing-mode instability. An interesting question is whether the same phenomenon can lead to a bifurcation of the current sheet into two or more parallel sheets. Such an instability (if it occurs) might offer an explanation of the appearance of multiple auroral arcs, at least when these cannot be attributed to the extreme convolution of a single arc so as to create the optical illusion of multiple structures.

Modulation of the diffuse aurora is presumed to result from modulation of the wave intensities responsible for scattering the auroral particles into the loss cone. This can happen, for example, if a ULF instability modulates the plasma density and/or magnetic-field strength near the magnetospheric equator and thereby modulates the growth rate for some VLF wave mode, either electromagnetic (Coroniti and Kennel, 1970) or electrostatic. The result could be a pulsating aurora. An extreme example of such modulation could occur if the ULF instability were to occur at zero frequency and be non-convective, as in the diamagnetic mirror instability (e.g, Scarf et al., 1967). Hasegawa (1969) has, of course, pointed out that the mirror instability becomes convective when the magnetic field is inhomogeneous, and it seems clear that a perpendicular electric field would also make the instability convective. However, the least convective excitations of the mirror instability would seem to be those for which the propagation vector is most nearly perpendicular to the drift velocity of the hot plasma, i.e., of the plasma that is making the mirror mode unstable. The result should be a family of striations, roughly parallel to the discrete-auroral oval, but in the diffuse aurora. These striations would be passed on in the usual way from (a) striations in the equatorial $\underset{\sim}{B}$-field intensity and hot-plasma density to (b) striations in the growth rates of electron-cyclotron waves, either electromagnetic or electrostatic, to (c) striations in the wave intensities to (d) striations in the electron-precipitation rate and (perhaps more importantly) in the resonant-electron energy required for precipitation to (e) striations in the optical characteristics of the diffuse aurora. Such a mechanism might account for the appearance of multiple "arcs" in the diffuse aurora of the post-midnight sector. The supply of electrons for precipitation would not necessarily be depleted by this process, since the drift shells of hot electrons and hot protons intersect obliquely with each other and with the drift shells of cold plasma.

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